# Silicon Radiation Damage and Expected Run II Lifetimes

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*Overview*

- Intro
- Silicon
  1. Leakage Current
  2. Depletion Voltage
- Data acquisition
  1. SVX3
  2. Port cards
- Summary

# Radiation concerns for Run IIa silicon

- Degradation of Signal/Noise
  1. Full signal collection may be difficult after high dose (depletion).
  2. Noise from increased leakage currents.

- Component Robustness
  1. Silicon sensors – a concern for L00, SVXII, and D0 90°
  2. Readout electronics (inner: SVX3 chip, hybrids) – possible concern for L00?
  3. Readout electronics (outer: port cards, DOIMs, etc) – next talk
  4. Single event upset – Not a problem with 0.8 $\mu$m process.

This talk will cover only recent estimates of depletion voltages and currents.

The oft-quoted numbers (from CDF3408) are a dose of 0.5 Mrad/fb$^{-1}$. This is based on leakage current measurements during Run 1a and is conservative. Is this still correct?

# Leakage Current Estimates

For the innermost layer of SVX and SVX′ ($r \approx$ 3.0 cm) leakage *vs* strip was found to be

$$I^{SVX} = 0.80\ nA/strip/pb^{-1} \quad (1)$$
$$I^{SVX'} = 0.63\ nA/strip/pb^{-1} \quad (2)$$

at 24±2 °C and with a radial dependence proportional to $r^{-1.68}$, where $pb^{-1}$ refers to delivered luminosity [CDF3937].

From an average of the equations above and converting to T = 15°C, r = 2.54 cm and strip volume to $2.79 \times 10^{-3}$ cm$^3$:

$$I_{L0}^{15°C} = I_{3.0cm}^{24°C} \left[\frac{2.79 \times 10^{-3}\ cm^3}{4.59 \times 10^{-3}\ cm^3}\right] \left[\frac{1}{2.265}\right] \left[\frac{2.54\ cm}{3.00\ cm}\right]^{-1.68} \quad (3)$$
$$= 0.25\ nA/strip/pb^{-1} \quad (4)$$

For L00 we use T = 5°C, r = 1.35 cm and strip volume to $1.13 \times 10^{-3}$ cm$^3$;

$$I_{L00}^{5°C} = I_{3.0cm}^{24°C} \left[\frac{1.13 \times 10^{-3}\ cm^3}{4.59 \times 10^{-3}\ cm^3}\right] \left[\frac{1}{5.963}\right] \left[\frac{1.35\ cm}{3.00\ cm}\right]^{-1.68} \quad (5)$$
$$= 0.11\ nA/strip/pb^{-1} \quad (6)$$

To find the fluence (in terms of 1 MeV neutron equivalent dose) we use the relation for current (at 20°C) and $I_{strip} = I_0 + \alpha \times \Phi \times Vol_{strip}$. Following CDF3937 we chose $\alpha_{\text{effective}} = 1.1 \times \alpha_\infty = 4.4 \times 10^{-17} A/cm$.

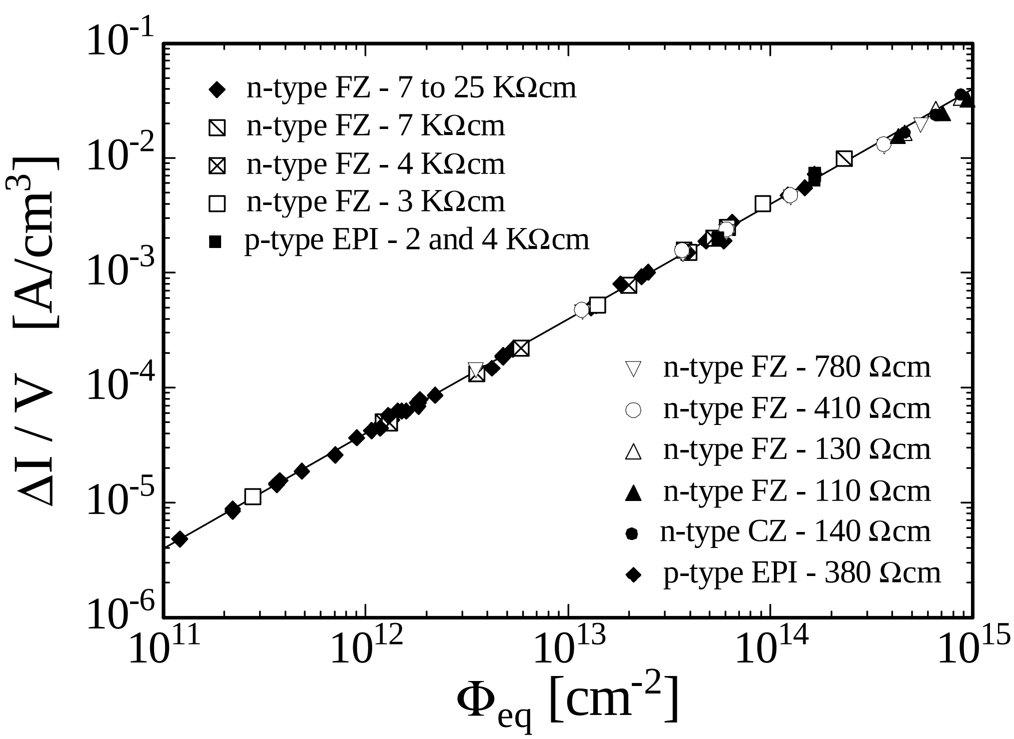
$$\Phi_{L0}^{1MeVn} = \frac{(0.25 \times 1.58)\ nA/strip/pb^{-1}}{\alpha_{\text{effective}} \cdot 2.79 \times 10^{-3} (cm^3/strip)} \quad (7)$$
$$= 0.32 \times 10^{13} (1MeVn)/cm^2/fb^{-1} \quad (8)$$

# Comparison to previous estimates

- This compares very favorably with previous (design) estimates.

  Using the average of Run Ia and Ib (the previous page):
  $$\Phi_{L0} = 0.32 \times 10^{13} cm^{-2}/fb^{-1} \quad (9)$$
  Numbers from CDF3408 (the ones everyone remembers):
  $$\Phi_{L0} = 0.75 \times 10^{13} cm^{-2}/fb^{-1} \quad (10)$$

- Why the change?
  1. Best (rather than conservative) estimate.
  2. Larger damage constant $\alpha_\infty$.



# Is a good V$_{dep}$ model really important?

- For L00, *no*

  1. Deterioration of charge collection efficiency should not cause problems at Tevatron fluences.
  2. Not a serious design or operational limitation.

- For SVXII, *yes*

  1. Double sided AC coupled silicon with 100V integrated capacitors; 200V max.
  2. Voltage drop across filter and biasing resistors should not be large.
  3. Microdischarge problems begin to occur above 170V.

- For D0 90°, *yes*

  1. Double sided AC coupled silicon with 100V integrated capacitors; 200V max.
  2. Moderate voltage drop, but higher voltage power supplies (so not a problem).
  3. Microdischarge problems with split biasing; 100V+30V.

# Depletion Voltage Prediction

Test beam studies limit the fluence to about $7 \times 10^{13}(1MeVn)/cm^2$.

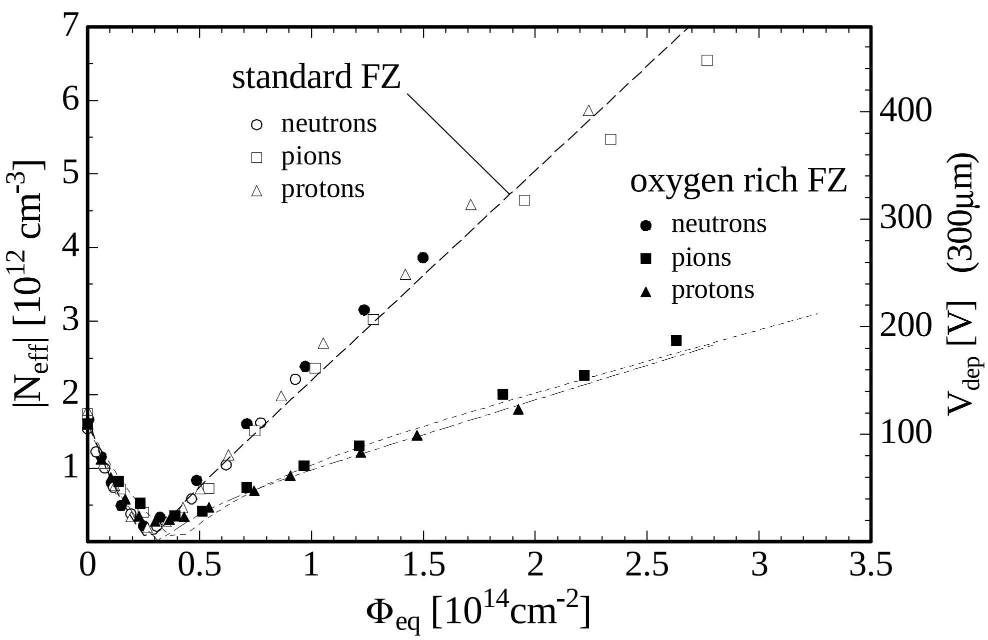



Figure 9: Dependence of $N_{eff}$ on the accumulated 1 MeV neutron equivalent fluence for standard and oxygen enriched FZ silicon irradiated with reactor neutrons (Ljubljana), 23 GeV protons (CERN PS) and 192 MeV pions (PSI).

# Depletion Voltage Prediction

The depletion voltage in a planar diode is given by

$$V_{planar} \propto d^2 \cdot |N_{eff}| \tag{11}$$

where $N_{eff}$ is the effective doping concentration, and

$$\Delta N_{eff}(\Phi, t, T) \approx N_C(\Phi) + N_y(\Phi, t, T). \tag{12}$$

This equation can be broken up into a stable defect portion and a reverse annealing portion as follows;

$$N_C(\Phi) = N_{C0}(1 - e^{-c\Phi}) + g_C \tag{13}$$

$$N_Y(\Phi, t, T) = N_{X0}(\Phi)(1 - \frac{1}{1 + N_{X0}(\Phi) k_0 e^{-E_a/k_B T} t}) \tag{14}$$

(for example A.Chilingarov *et al*, NIM A360 432-437). Now for strip sensors,

$$V_{depletion} = V_{planar}(1 + 2\frac{p}{d} f(w/p)) \tag{15}$$

To predict the depletion voltage as a function of dose, we need to measure $N_{C0}$ for Hamamatsu silicon.

# Depletion Voltage Modeling (continued)

- Model includes both the short term beneficial annealing and the long term reverse annealing.

- Model also includes an estimate of the 'overvoltage' required (from NIM A 342 (1994) 90). This is typically a small effect.

- Damage constants used are listed in the table below. They are averages of several measurements compiled by Feick (in his dissertation).

| Parameter | | Neutrons | Protons | Pions |
|---|---|---|---|---|
| $g_Y$ | $(10^{-2}\text{cm}^{-1})$ | 4.6±0.3 | 5.80±0.3 | 8.1±0.5 |
| $g_C$ | $(10^{-2}\text{cm}^{-1})$ | 1.77±0.07 | 1.15±0.09 | 2.01±0.05 |
| $N_{C0}$ | $(10^{11}\text{cm}^{-3})$ | 2.0 | 6.3 | 3.9 |
| $c$ | $(10^{-13}\text{cm}^{2})$ | 2.29±0.63 | 0.96±0.19 | 1.64±0.29 |
| $E_a$ | (eV) | | 1.31±0.04 | |
| $k_0$ | $(\text{cm}^3\ \text{s}^{-1})$ | | 520 (128 to 2110) | |
| $\alpha_\infty$ | $(10^{-17}\text{cm}^{2})$ | 2.86±0.18 | 2.22±0.10 | 3.89±0.20 |

- $g_Y$, $g_C$, and $N_{C0}$ – These parameters determine the variation of $N_{eff}$ as a function of fluence (1 MeV neutron equivalent dose).

- $c$ – the 'donar removal' constant

- $E_a$ – activation energy

- $k_0$ – frequency factor

- $\alpha_\infty$ – reverse current normalized to the fluence

# Parameters used the $V_{dep}$ model

| Parameter | L00 | L0 | L1 | L2 | D90 |
|---|---|---|---|---|---|
| n width ($\mu$m) | 50 | 30 | 20 | 15 | 22 |
| n pitch ($\mu$m) | 50 | 141 | 125.5 | 60 | 153.5 |
| p width ($\mu$m) | 8 | 14 | 14 | 15 | 17 |
| p pitch ($\mu$m) | 25 | 60 | 62 | 60 | 50 |
| $V_{dep}$ initial (V) | 70 | 65 | 65 | 25 | 30 |
| temperature (C) | 5 | 15 | 15 | 15 | 10 |

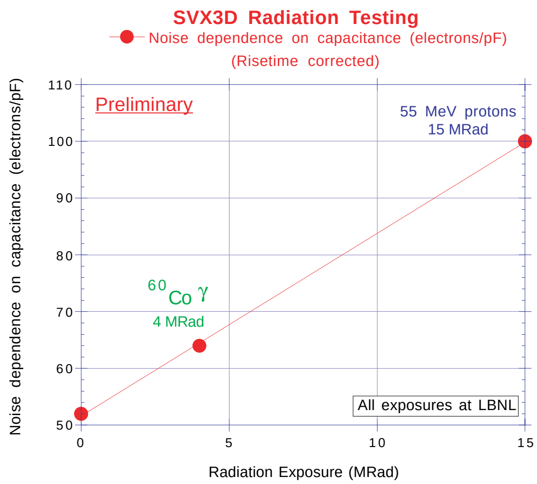
A scaling of the fluence is conduced ($r^{-1.68}$) in the plots below to account for the increased dose in the inner layers. The horizontal axis corresponds to $1.0 \times 10^{13}$ particles (protons, pions) per cm$^2$.

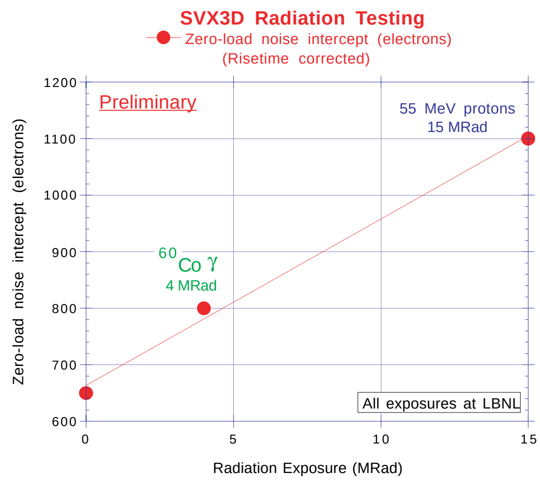
$$
\begin{aligned}
\text{L00} &= (2.54/1.35)^{1.68} = 2.75 \\
\text{L0} &= (2.54/2.54)^{1.68} = 1.00 \\
\text{L1} &= (2.54/4.12)^{1.68} = 0.44 \\
\text{L2} &= (2.54/6.52)^{1.68} = 0.21 \\
\text{D90} &= (2.54/2.70)^{1.68} = 0.90
\end{aligned}
$$

Plots assume $1.0 \times 10^{13}$ dose per year on L0, and the dose for other layers is scaled as shown above.

# SVX3 chip rad damage measurements

Next talk, but...




Assuming an effective charge collection of 20,000 electrons, we can estimate the signal/noise versus fluence from the plots above:

- At 4 MRad (same as $^{60}$Co study):

$$\begin{aligned} noise &= 64e/pF \times 20pF + 780e \\ &= 2060e \\ signal/noise &= 10 \end{aligned} \tag{16}$$

- At 8 MRad:

$$\begin{aligned} noise &= 78e/pF \times 20pF + 900e \\ &= 2460e \\ signal/noise &= 8 \end{aligned} \tag{17}$$

- At 12 MRad:

$$\begin{aligned} noise &= 90e/pF \times 20pF + 1000e \\ &= 2800e \\ signal/noise &= 7 \end{aligned} \tag{18}$$

Chip is operable at high fluence, but signal/noise is bad.

# Port card radiation damage estimates

Next talk, but...

Assuming that the port card will have troubles at 400 krad, we can get a rough idea of the comparison between port card and sensor damages by just...

$$400krad \times \frac{3.75 \times 10^{13}}{1Mrad} \approx 1.5 \times 10^{13} n/cm^2/fb^{-1}$$

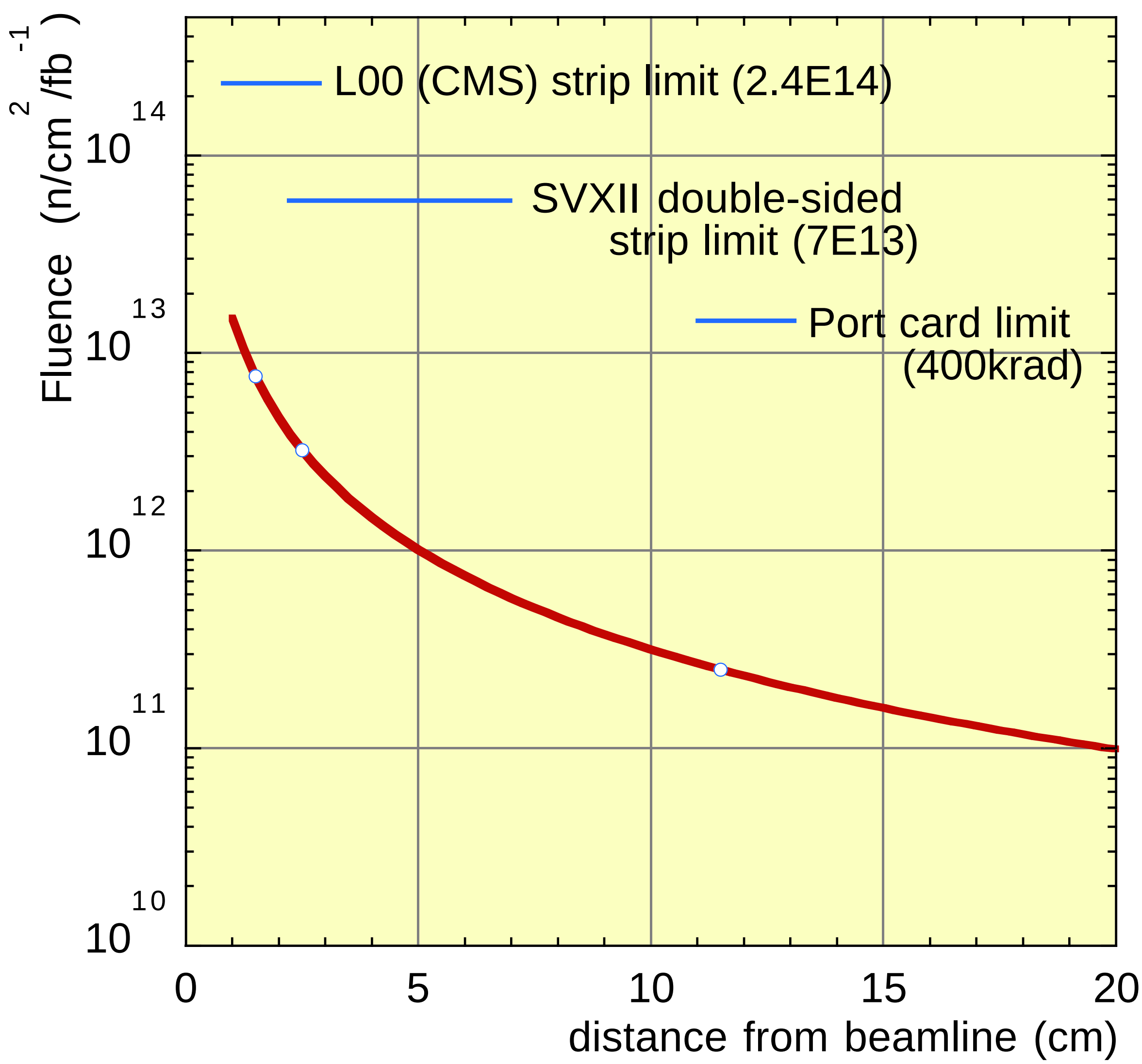
# How do you compare NIEL to charged rad damage?

Can either do a full simulation of the backgrounds, or you can pick a few specific particle types and energies, or...

CDF3937 has an independent estimate from the ratio of the elastic and low mass diffractive cross sections (evaluated at r=1cm):

$$\frac{\Phi^{CDF}_{1MeVn}}{\Phi^{CDF}_{charged\ rad\ damage}} \approx 0.62 \pm 0.19 \tag{19}$$

This functions as an 'average' hardness factor and allows us to compare accumulated damage on the same timescales...


L00 (CMS) strip limit (2.4E14)
SVXII double-sided strip limit (7E13)
Port card limit (400krad)
Fluence (n/cm$^2$/fb$^{-1}$)
$10^{14}$
$10^{13}$
$10^{12}$
$10^{11}$
$10^{10}$
0
5
10
15
20
distance from beamline (cm)

# Conclusion

This result implies a longer lifetime for the silicon. The ratio of radiation dose on the silicon and luminosity had been overestimated.

But now some mismatches exist...

- our capabilities do not match our stated Run IIa goal of $> 4\text{fb}^{-1}$,
- we do not match well with D0, which will die sooner, and
- neither experiment matches the goals of the lab (2 $\text{fb}^{-1}$ in 2 years).